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Initial investigation of B_4C–TiB_2 composites as neutron absorption material for nuclear reactors

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Abstract

In this study, a specifically designed B_4C–TiB_2 composite with the typical microstructural feature of a TiB_2 network (cages) that encapsulates a B_4C matrix was fabricated by the molten-salt and spark plasma sintering (SPS) method. The finite-element (FE) calculation results show that the connected TiB_2 cages constitute a thermally conductive network, which effectively improves the overall thermal conductivity of the composite; these results agree well with the experimental results. Moreover, the Vickers indentation results reveal that the TiB_2 network (cages) can effectively impinge/block the propagation of cracks, which increases the composite toughness. The composite was subjected to helium (He) ion irradiation to simulate the situation in which the B_4C–TiB_2 composites serve as neutron absorption material, and for which case a high quantity of He atoms is produced by the B^{10} (n, α) Li^7 nuclear reaction. According to the transmission electron microscopy (TEM) results, the interfaces between TiB_2 and B_4C act as effective sinks for He atoms, and are preferential nucleation sites for He bubbles. The theoretical and experimental results show that when the B_4C–TiB_2 composites serve as neutron absorption pellets in nuclear reactors, they exhibit a better resistance to their disintegration than pure B_4C pellets. Consequently, the performance of the control rods of nuclear reactors can be improved.

Keywords: neutron absorber; B_4C pellet; He irradiation; crack propagation; finite element.

1. Introduction

B_4C is widely used as a neutron absorption material for control rods (CRs) in many nuclear reactor systems, in particular in fast reactor systems [1] (e.g., Phenix (France), BN (Russia), JOYO (Japan), ALMR, FFTF (United States)) owing to its high melting temperature, outstanding thermal stability, good mechanical properties, and the high neutron absorption cross section of ^{10}B; B_4C neutron absorbers play an important role regarding the performance of CRs by, for example, adjusting the reactivity compensation during the normal operation cycles of nuclear reactors, initiating/terminating an operation cycle for refueling or reactor component maintenance, and rapidly shutting down the reactor if abnormal conditions occur. Therefore, B_4C neutron absorbers are of primary importance for the safe and efficient operation of nuclear reactors.

In many CR designs (e.g., JOYO), B_4C materials are usually presented in the form of pellets. However, during the operation lifetime of CRs, B_4C pellets often fracture into pieces and even powders [2]. These fractured B_4C pellet pieces progressively fill the gaps between the pellets and cladding materials, which accelerates the absorber-cladding mechanical interaction [2]. This leads to an incompatibility between the cladding materials and other components of reactors (e.g., induced absorber swelling cladding cracking (IASCC)) and shortens the CR

lifetime. Moreover, the cracked materials are very sensitive to the subsequent radiation-assisted dissolution (i.e., radiolysis effects [3-5]). Regarding water-cooled nuclear systems, when cooling water leaks into the pellet capsule owing to IASCC-induced cracking [6], the radiolysis effect accelerates the dissolution of the absorber materials and promotes the disintegration of B_4C pellets [5]. Both effects degrade the CRs and safe operation of nuclear reactors.

According to previous research studies, the disintegration of bulk B_4C ceramic pellets is closely associated with the thermal-gradient-induced macrocracks and swelling-gradient-induced microcracks [7]. During the service lifetime of CRs, the (n, α) nuclear reaction releases an average energy of 2.78 MeV per event [1]; the most energy is deposited within the B_4C matrix. For instance, at a CR burnup of 10^{22} cap/cm^3 per year, a volume power of 1.5×10^2 W/cm^3 is deposited in the B_4C pellets. Owing to the low thermal conductivity of B_4C and the high heat-generation rate caused by the ^{10}B (n, α) ^7Li reaction, the temperature gradient of B_4C pellets can reach up to 10^3 K/cm. Such a high temperature gradient causes a great thermal stress and results in thermal-stress-induced macrocracks. Moreover, a high quantity of He atoms produced by the transmutation reaction accumulate in the form of flat lenticular He bubbles [8,9]. These He bubbles cause significant volume swelling. When the neutron absorption pellets are placed in

thermal neutron reactors, owing to the self-shielding effect [7,10], the burnup of the pellet periphery is usually stronger than that of the interior. Because the He atom production is proportional to the burnup level, a gradient distribution of He bubbles leads to a steep swelling gradient of the B_4C material and an abrupt local strain [7]: the consequence are swelling-gradient-induced microcracks. In general, the released heat and He atoms produced by the ^{10}B (n, α) ^{7}Li reaction are two factors that lead to the formation of cracks. Both factors promote the formation of macro-scale cracks and facilitate the crack propagation through pellets, which result in their disintegration [2,11].

Therefore, it is of vital importance to improve the thermal conductivity and irradiation-induced swelling resistance of B_4C absorber materials to guarantee the good long-term performance of CRs and a safe and efficient operation of nuclear reactors. B_4C–diborides composites have been explored a long time ago to improve the performance of B_4C in the irradiation field. For example, B_4C–HfB_2 composite was designed to improve fracture toughness [12, 13] and the thermal-mechanical properties of the neutron absorber [12]. In this study, a low economic cost and honeycomb-structured B_4C–TiB_2 composite was elaborated to attain the aforementioned objective. The main feature of the composite is a highly thermally conductive cage-like TiB_2 network that encapsulates conventional B_4C matrix grains. TiB_2 has a high melting point (3498 K),

exceptional hardness (25-35 GPa), highly thermal conductivity, excellent wear resistance, a low thermal expansion coefficient (4.6×10^{-6} K^{-1}, which is almost the same as that of B_4C, 4.5×10^{-6} K^{-1}), and a high oxidation resistance [14-18]. Owning to the inimitable characteristics of TiB_2, it is therefore selected as the cage-like structure of the B_4C–TiB_2 composites. The good features of conventional B_4C material are maintained, and the thermal conductivity of the composite is significantly improved with respect to that of the pure B_4C material. In addition, the composite exhibits many interfaces.

The B_4C–TiB_2 composites were subjected to He ion irradiation to simulate the situation in which the B_4C–TiB_2 composite is exposed to a high neutron flux, and a high quantity of He atoms is produced by the (n, α) reaction. Moreover, a series of post-irradiation analyses and FE calculations were conducted to evaluate the behavior of the B_4C–TiB_2 component in a nuclear reactor environment.

2. Experimental details

2.1. Material synthesis

A two-step synthesis method was employed to synthesize the B_4C–TiB_2 composite [19]. In the first step, Ti and B_4C powders were mixed with NaCl and KCl in an Al_2O_3 crucible. The mixtures with initial B_4C/Ti molar ratios of 6:1, 4:1, and 2:1 were exposed to an Ar atmosphere at 1273 K. After the (1) and (2) in-situ reactions in the melted salt bath, a

uniform TiB_2 coating occurred on the B_4C particles. The remnant NaCl, KCl, and other impurities were washed away with deionized water, and the samples were subsequently dried to obtain dry TiB_2-coated B_4C powders. Note that the melt point of NaCl and KCl mixing is low (~ 933 K) and the liquid mass transfer mode between B_4C and Ti in the molten salts guarantees the uniform nucleation and growth of TiB_2 on the surface of B_4C particles. Therefore, the NaCl and KCl were employed as the medium for reactions.

$$3Ti + B_4C \rightarrow TiC + 2TiB_2 \quad (1)$$

$$2TiC + B_4C \rightarrow 2TiB_2 + 3C \quad (2)$$

In the second step, the mixtures containing uniformly TiB_2-coated B_4C powders with different TiB_2 contents were sintered in a spark plasma sintering (SPS) system (SPS-20T-15, Chen Hua) with the same procedure to obtain three cylindrical bulk samples with diameters of 13 mm and heights of 2 mm (denoted as S1, S2, and S3). In the SPS procedure, the heating rates are 50 K/min from RT to 1673 K, and 25 K/min from 1673 K to 1973 K, respectively. The holding time and temperature are 10 min and 1973 K, respectively. The pressure during the holding stage is 45 MPa. The cooling rate is 50 K/min from the holding temperature to RT. Each bulk sample has a relative density of 100%. The volume fractions of TiB_2 phases in B_4C-TiB_2 composites are determined by the equation (3).

$$\frac{V_{TiB_2}}{V_t} = \frac{\frac{m_{TiB_2}}{\rho_{TiB_2}}}{\frac{m_t}{\rho_t}} = w_{TiB_2} \cdot \frac{\rho_t}{\rho_{TiB_2}} \qquad (3)$$

Where V_{TiB_2} and V_t are the volume of TiB_2 phases and the B_4C-TiB_2 composites, respectively. w_{TiB_2} is the weight percent of TiB_2 measured by using XRD, the calculated weight percent of TiB_2 for S1, S2 and S3 are 18 %, 26% and 44%, respectively. ρ_{TiB_2} (4.5 g/cm^3) is the density of TiB_2 and ρ_t is the density of the B_4C-TiB_2 composites (2.637, 2.796 and 3.051 g/cm^3 for S1, S2 and S3, respectively). The density of the B_4C-TiB_2 composites were measured by and Archimedes method. The chemical composition and the calculated volume fraction of each sample are shown in Table 1.

2.2. Vickers indentation tests and irradiation procedure

A pyramidal diamond tip with an apical angle of 136° was used to perform Vickers indentation tests. The tests were performed on the surface of the virgin samples to investigate the crack propagation behavior in the composite. During the indentation tests, the maximal load was set to 9.8 N, and the holding time was 15 s. Each indentation was set more than 100 μm apart to avoid an overlap of the indentation-induced deformations or crack outspread regions.

The He ion irradiation procedure was conducted in a terminal chamber with a 320 kV multidiscipline research platform for highly

charged ions at the Institute of Modern Physics (IMP), Lanzhou, China. Samples S1, S2, and S3 were irradiated with 500 keV He ions with 1×10^{17} ions/cm^2 at 773 K. After the irradiation process, the samples were annealed at 1273 K for 25 min in a vacuum of 10^{-5} Pa. In addition, Stopping Range of Ions in Matter (SRIM) codes were conducted with the Kinchin–Pease quick-calculation mode to predict the distribution of the He atoms and displacement damage in B_4C and TiB_2, respectively. The calculated distribution is a function of the penetration depth, as shown in Fig. 1; the Bragg peak with a He concentration of 8.92×10^{21} cm^{-3} (7.02%) is located at a depth of ~ 1.38 μm in the B_4C material, and 7.18×10^{21} cm^{-3} (6.14%) at a depth of ~ 1.56 μm in TiB_2 material, respectively.

2.3. Characterization

The morphology of the sample surface and Vickers indentation impression were recorded by scanning electron microscopy (SEM, Thermo Fisher Quanta FEG 250). In addition, the focused ion beam technology (Thermo Fisher, Helios G4 CX) was employed to lift up thin foils for the transmission electron microscopy (TEM) analysis. The thin foils were analyzed with a Talos F200X TEM at 200 kV in the bright-field mode, and a HV-1000 indentation test machine (Shanghai Lianer Testing Equipment Corporation) was used to perform the Vickers indentation tests.

3. Results and discussions

Before the SEM analysis, the composites were mechanically polished with diamond papers (from 800 to 12500 grit) until mirror-like surfaces were obtained. Fig. 2 shows the typical SEM images of the B_4C–TiB_2 composites with TiB_2 volume fractions of 10.5% (Fig. 2(a)), 16.2% (Fig. 2(b)), and 29.8% (Fig. 2(c)). The white contrast indicated by black arrows in the SEM images are TiB_2 phases, and the left, dark contrast represents B_4C grains. The TiB_2 phases are distributed along the B_4C grain boundaries. With increasing TiB_2 phase volume fraction, the fraction of isolated TiB_2 particles decreases, and more and more TiB_2 phases along the grain boundaries become connected, which results in an interconnected network from the two-dimensional (2D) point of view (Fig. 2(c)). Therefore, from the three-dimensional point of view, the TiB_2 network forms a cage-like structure, which encapsulates the B_4C matrix grains. The average thickness of the TiB_2 network of S3 is 0.9 μm, and the statistical measurement based on the line-intercept method [20] reveals that the mean grain sizes of B_4C in the S1, S2, and S3 samples are 9.5, 8.6, and 6.4 μm, respectively. Thus, the TiB_2 fraction increases at the expense of consumed B_4C.

To evaluate the effect of the TiB_2 network (cages) and its volume fraction on the heat transfer performance in the B_4C–TiB_2 composites, a series of numerical studies based on the typical microstructures of pure B_4C and B_4C–TiB_2 composites were implemented in the FE program

ABAQUS. The geometric constructions of the 2D pure B_4C and B_4C–TiB_2 composites FE model is shown in Fig. 3. A thermal continuity constraint was defined at each interface to connect the B_4C and TiB_2 domains without heat dissipation. An initial temperature of 773 K was assigned to the entire computational region to simulate the reactor environment temperature, and 1273 K (boundary condition) was assigned to the left end of each model to generate a stable heater source; the other boundary conditions were adiabatic boundary conditions. The temperature dependence of the physical parameters of B_4C and TiB_2 used in the numerical calculation are listed in Table 2 [18,21].

The temperature distributions used with different time scales for the pure B_4C and B_4C–TiB_2 composites models are shown in Fig. 4. The temperature distribution in pure B_4C is homogeneous along the vertical direction, and the isotherms are perpendicular to the horizontal axis. Whereas the temperature in the B_4C–TiB_2 composites presents an irregular gradient distribution. Furthermore, the temperature gradient in the B_4C–TiB_2 composites with a high TiB_2 volume fraction is lower than that of the low TiB_2 volume fraction. Particularly, the maximum temperature gradient appears in pure B_4C. Thus, heat is transmitted faster in the B_4C–TiB_2 composite than in the pure B_4C, the higher the volume fraction of TiB_2, the faster the heat transfers, which is consistent with the experimental results in [19].

To compare the heat transfer performance of the four structures quantitatively, the temperature variations at the middle point of the right-end boundary in each model are presented with respect to time in Fig. 5. The heating rate in the B_4C–TiB_2 composite with higher TiB_2 volume fraction is higher than that of lower ones. For example, the temperature at point P_3 in the B_4C–TiB_2 composite with the highest TiB_2 volume fraction (29.8%) reaches 1181 K within 1 μs, while the temperature at point P_0 in the pure B_4C becomes only 1076 K within the same time. The FE analysis results demonstrate that the lower temperature gradient caused by the faster heat propagation in the B_4C–TiB_2 composites can be ascribed to the existence of the TiB_2 network in the B_4C matrix, which has a higher thermal conductivity. If the composites are used as neutron-absorbing pellets in nuclear reactors, their high thermal conductance can rapidly cool the local high temperature caused by the nuclear reactions and greatly reduce the thermal stress caused by the thermal gradient, which reduces the risk of structural failure.

To further determine the equivalent average parameters and average heat conducting characteristics of the B_4C–TiB_2 composite, the equivalent homogeneous models with all the homogenized model parameters, such as conductivity, specific heat and density, determined by the volume-weighted-average were implemented for the three cases of

different TiB_2 volume fractions (10.5%, 16.2% and 29.8%). Taking the temperature of the middle point of the right-end boundary as the assessment during simulation from 0.2 to 1 μs, the comparison of the results calculated from real composite structure and equivalent homogeneous models are summarized in Table 3. It can be seen that the results of the equivalent homogeneous models are slightly overestimated for the three cases, but the maximum relative error is less than 5%, which indicates that the simple volume-weighted-average method can be used to roughly predict the equivalent parameters and average heat conducting characteristics of the B_4C–TiB_2 composite for variational volume fraction. It demonstrates the expected conductivity enhancement brought by the interconnectivity of the TiB_2 phases as well.

In real nuclear reactors, the thermal gradient and He swelling-induced crack propagation in B_4C materials are mainly responsible for the disintegration of B_4C pellets in fast neutron reactors and in thermal neutron reactors, respectively. To investigate the effect of the TiB_2 network (cages) on the crack propagation behavior in the B_4C–TiB_2 composites, Vickers indentation was employed to simulate the external stress that was applied to the B_4C–TiB_2 composites.

The typical Vickers indentation marks on the surfaces of S1, S2, and S3 are shown in Figs. 6(a), (b), and (c), respectively. The beginnings and endings of the cracks are indicated by double-headed arrows. Note that in

the Fig. 6(c), the gradient of sunken area is steep, outline of the Vickers indentation impression is irregular, but four cracks of the indentation are obvious. Therefore, each crack length is measured from the end of the crack, and along the inverse direction of crack propagation to the point where crack origins from the steeply sunken area (i.e. the indentation impression area). At a load of 9.8 N, the length of the cracks on S1 range from 20.7 to 27.9 μm; those on S2 and S3 range from 12.8 to 20.3 μm and 6.8 to 13.5 μm, respectively. The statistical results of the cracks show that the average values are 22.9 ± 2.8, 16.1 ± 4.3, and 12.2 ± 3.8 μm for S1, S2, and S3, respectively. Fig. 7 presents the statistical results of the crack lengths on S1, S2, and S3, respectively. Evidently, the crack lengths decrease with increasing TiB_2 volume fraction. Thereby the statistical results prove that the TiB_2 phase distribution along the grain boundaries can impinge/block the crack propagation.

Figs. 8(a) and (b) present the enlarged SEM images of the crack propagation paths in S1 and S3, respectively. The white contrast in Figs. 8(a) and (b) are TiB_2 phases: the TiB_2 phases in Fig. 8(a) are isolated particles, which are distributed in the B_4C matrix; the TiB_2 phases in Fig. 8(b) are interconnected, thereby forming a network (cages). The solid arrow in Fig. 8(a) indicates clearly that the propagating crack departs from its original straight trajectory and curves along the B_4C/TiB_2 interface, thereby proving that the isolated TiB_2 islands in the B_4C matrix

309 can redirect the crack propagation. A similar phenomenon was reported in
310 [22]. In this study, the network (cages) topography in Fig. 8(b) clearly
311 shows that the crack propagates through the TiB_2 walls (dashed arrows 2
312 and 3) and extends along the interface between the B_4C and TiB_2 phases
313 (dashed arrow 1), which facilitates the energy release of the crack tip.
314 This is confirmed by the shorter crack length (12.2 ± 3.8 μm) of S3 than
315 those of S1 (22.9 ± 2.8 μm) and S2 (16.1 ± 4.3 μm), as shown in Fig. 6.

316 It can be concluded that there are two underlying ways in which the
317 TiB_2 phases affect the crack propagation in B_4C–TiB_2 composites: first,
318 when the volume fraction of the TiB_2 phase is low, TiB_2 distributes in the
319 B_4C matrix as isolated particles (shown in Fig. 8(a)), and when the
320 propagation of a crack tip encounters a TiB_2 particle, the crack moves
321 along the B_4C/TiB_2 interface, prolongs the crack propagation length and
322 dissipates more energy, finally results in an improvement of the fracture
323 toughness of the B_4C–TiB_2 composites. Similar dissipation mechanisms
324 at the B_4C/TiB_2 interfaces are also found in Refs. [23, 24]. Second, when
325 the volume fraction of the TiB_2 phase is high, the TiB_2 phase forms an
326 enclosed cage-like structure that encapsulates the B_4C grains (Fig. 8(b)).
327 Thus, the cracks have to penetrate the TiB_2 walls before extending along
328 the B_4C/TiB_2 interfaces or must propagate through the neighboring B_4C
329 grains. According to the model of Cook et al. on crack propagation in
330 brittle systems [25], additional energy is required to deflect the crack

propagation and initiate secondary crack propagation across the interface; the primary crack requires much energy.

To quantitatively measure the fracture toughness of the B_4C-TiB_2 composites, following equations are used [26]:

$$K_{IC} = 0.016(E/H_V)^{0.5} P c^{-1.5}, \quad (4)$$

where

$$H_V = \frac{1.8544 \times P}{4a^2 \times 1000}, \quad (5)$$

in which E is the Young's modulus, H_V the Vickers hardness, P the Vickers indentation load, and a and c are the half length of the residual Vickers indenter impression diagonal and half length of the radial crack diagonal, respectively. The fracture toughness of the composites K_{IC} were calculated to be 3.06 ± 0.28 (MPa·$m^{1/2}$), 3.81 ± 0.33(MPa·$m^{1/2}$), and 4.38 ± 0.67 (MPa·$m^{1/2}$) for S1, S2, and S3, respectively. In other words, increasing the TiB_2 volume fraction and optimizing the distribution of TiB_2 can impinge/block the propagation of cracks and improve the fracture toughness of the B_4C–TiB_2 composites. This promotes the integration of B_4C pellets and improves the CR performance in the harsh environments of nuclear reactors.

He behavior of the composites under irradiation conditions is important for the evaluation of the composites serving in the reactors, however, it was seldomly studied. Therefore, we conducted He ions irradiation on the composites and initially investigated the He behavior by

353 TEM observation.

354 The TEM images in Fig. 9 show the He bubble distribution and
355 morphology in B_4C phase of samples S1, S2, and S3. The images were
356 recorded with the same underfocus of 2.8 μm. The He bubbles, which are
357 small bright dots in the images, are located within a band area. The width
358 of He bubbles deposition band is smaller than that of the implanted band
359 as calculated by SRIM, similar phenomenon is observed by Motte et al.
360 [8]. It is suggested that this is due to the different depths of the He ions
361 induced damage profile and the He ions implanted profile. In the area of
362 the damage profile, lot of vacancies were introduced by energetic ions
363 collision, while in the area of He atoms implanted band, He atoms greatly
364 outnumbered the vacancies. In the overlapped areas (the width of which
365 was smaller than the implanted band as calculated by SRIM), abundant
366 vacancies and He atoms promoted the formation of He-vacancy clusters
367 and increased the density of He bubble germs. After annealing,
368 He-vacancy clusters evolved into visible He bubbles under TEM
369 observation and formed a bubbles band in the overlapped area. Moreover,
370 Gillet et al. found that the dissociation energy of He-vacancy is $\sim$ 2 eV,
371 the high energy barrier inhibited the He diffusion by the formation of
372 He-vacancy clusters [27], and this explained that no He bubbles outside
373 the band area can be found (excepted the He bubbles in the grain
374 boundaries).

The He bubbles in the bubbles band are small and dense; such feature has been argued to arise partially from the diffusion behavior of He atoms in B_4C. According to Refs. [27-30], He atoms must overcome a high energy barrier to migrate even through the most probable migration paths owing to the intrinsic chemical bond and lattice structure of B_4C. Schneider et al. discovered that He atoms prefer to migrate between <111> planes by first-principle calculations. Moreover, they discovered that the activation energy of He ion diffusion is approximately 2 eV [28], which is consistent with the experimental results in [30]. The 2 eV migration energy means that the aggregation of He atoms in B_4C materials is retarded and explains the observation of small-sized He bubbles in this study rather than large-sized He bubbles in metals under similar irradiation conditions [31].

The He bubbles that are distributed along the interfaces are bigger than the bubbles distributed in the B_4C and TiB_2 grains (however, bubbles along the TiB_2–TiB_2 interface are not investigated in this study), as shown in Fig. 10. This is due to the special structure of the interface. Misfits in the lattice structure of the interfaces contain plenty of open volume [32], which provides adequate free space for the deposition of irradiation-induced point defects (e.g., vacancies, interstitials, transmuted elemental atoms) [33]. Owing to the high binding energy between vacancies and He atoms (~ 2 eV [27,28]), the open volume of interfaces

397 can act as efficient trapping sites for He and preferential nucleation sites
398 for He bubbles [8,9,34]. Therefore, once the He atoms are captured by the
399 interfaces, they cannot easily be released within the temperature range
400 investigated in this study. As shown in Fig. 10, no He bubbles depleted
401 zone was detected, which is consistent with the results of Motte et al.'s
402 work [28] that it was hard for He atoms to diffuse through or in the B_4C
403 grain boundaries below 1373 K. This might prove that long-range He
404 diffusion is negligible at 1273 K. Moreover, TEM image in Fig. 10 shows
405 that He bubbles deposition band in B_4C is closer to the surface than that
406 in TiB_2, this phenomenon is also consistent with SRIM calculation as
407 shown in Fig. 1 that the overlap of He distribution and damage profile is
408 shallower in B_4C than that in TiB_2.

409 In a realistic environment of nuclear reactors, increasing the density
410 of sinks for the precipitation of He atoms is an effective way to suppress
411 the formation of large He bubbles [35], and reduce the He-induced
412 property degradation (e.g. He embrittlement). Therefore, the network
413 (cages) of the TiB_2 phases provides numerous sinks for He precipitation,
414 which might inhibit the formation of large He bubbles, and mitigate the
415 effects of He-accumulation-induced shear stress at interfaces, and the
416 resulting microcracks, especially in the thermal neutron reactors.
417 However, other factors may affect performance of the B_4C–TiB_2
418 composites, such as shear stress induced by He accumulation at the

interfaces, different thermal dilation between B_4C and TiB_2. To have a better evaluation of the B_4C–TiB_2 composites in a realistic environment, a detailed numerical evaluation will be carried out in the future study.

As an important component of the B_4C–diborides composites, the behavior of diborides under irradiation environment is very crucial to the performance of composites. Cheminant et al. conducted neutron irradiation on HfB_2, and found that porosity appeared at grain boundaries, and resulted in a decrease of the thermal diffusivity [36], which lead to the degradation of B_4C–HfB_2 composites. Regarding the TiB_2 in this study, despite the inimitable merits of TiB_2, however, its irradiation behavior was seldomly studied, which is very important for the application of TiB_2 as neutron absorbers. To the best of our knowledge, only two studies reported the microstructural evolution of TiB_2 under irradiation conditions [37, 38]. Therefore, a systematic study on the irradiation tolerance of TiB_2 is needed, which will be part of our future work.

3. Conclusion

To improve the performance of B_4C neutron absorption material in nuclear reactors, a set of property-optimized B_4C–TiB_2 composites were designed and fabricated through a combination of the molten-salt and SPS methods. The TiB_2 phase distributes along the B_4C grain boundaries and forms a connected network (cages), which encapsulates the B_4C

matrix phase. The thermal conductivity and fracture toughness of the B_4C–TiB_2 composites are greatly improved owing to the special cage-like structure. The FE analyses show that the connected TiB_2 network promotes the heat transfer and improves effectively the overall thermal conductivity of the B_4C–TiB_2 composite. The improved thermal conductivity results in a lower thermal stress, which mitigates thermal-stress-induced crack propagation.

Vickers indentation tests were performed on the composites to study the crack propagation behavior. The TiB_2 network (cages) can effectively impinge/block the crack propagation, thereby improving the composite fracture toughness. This is important for maintaining the integration of B_4C–TiB_2 composites if the composite serves as neutron absorption material in nuclear reactors.

Moreover, He ion irradiation was used to investigate the He behavior in the composites and to simulate the situation in which a high quantity of He is produced by the B^{10} (n, α) Li^7 nuclear reaction. The TEM results show that the interfaces of B_4C and TiB_2 are effective trapping sites for He atoms and nucleation sites for He bubbles. Note that in a fast neutron reactor, the ballistic damage induced by energetic neutrons scattering and the nuclear reaction products (e.g., He, Li) scattering are much higher than the sole He ions implantation, this leads to a higher vacancy/He ratio and the possible consequences on the defects dynamics [28].

Overall, this study provides a synthesis method for fabricating neutron absorption materials for the application in nuclear reactors. The special property-optimized $B_4C–TiB_2$ composites with designed microstructure exhibit a better resistance to disintegration under irradiation and in the thermodynamic environment of nuclear reactors. In addition, they have a great potential for the application as neutron-absorbing pellets in nuclear reactors.

In the future study, other issues will be addressed to have a comprehensive evaluation of B_4C-TiB_2 composites under irradiation conditions. For example, helium behavior in TiB_2 and irradiation resistant property of TiB_2, effects of the special cage-like structure and TiB_2 content on He diffusion and release during annealing, other synthesis routes to optimize the structure and properties of the $B_4C–TiB_2$ composites, influence of He bubbles aggregation along the $B_4C–TiB_2$ and $TiB_2–TiB_2$ interface on the thermal conductivity of the composites and the crack propagation behavior, etc.

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Data availability

The raw data required to reproduce these findings cannot be shared at this time as the data is part of an ongoing study. The processed data required to reproduce these findings cannot be shared at this time as the data is part of an ongoing study.

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575 Figure captions

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582 pure B_4C model; (b)-(d) B_4C–TiB_2 composite model based on SEM
583 image of sample S1, S2 and S3, respectively; light and dark contrasts
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608

609 Table 1. Molar ratio of raw B_4C powder and Ti powder for molten-salt
610 reaction, volume fraction of TiB_2, weight percent of TiB_2, B_4C and C in
611 synthesized bulks.

Samples	Molar ratio (B_4C:Ti)	Volume fraction of TiB_2	Weight percent of TiB_2	Weight percent of B_4C	Weight percent of C
S1	6:1	10.5%	18.0%	80.4%	1.6%
S2	4:1	16.2%	26.0%	72.0%	2.0%
S3	2:1	29.8%	44.0%	52.0%	4.0%

612 Table 2. Material properties of B_4C and TiB_2 used in heat transfer

613 analysis [16, 19]

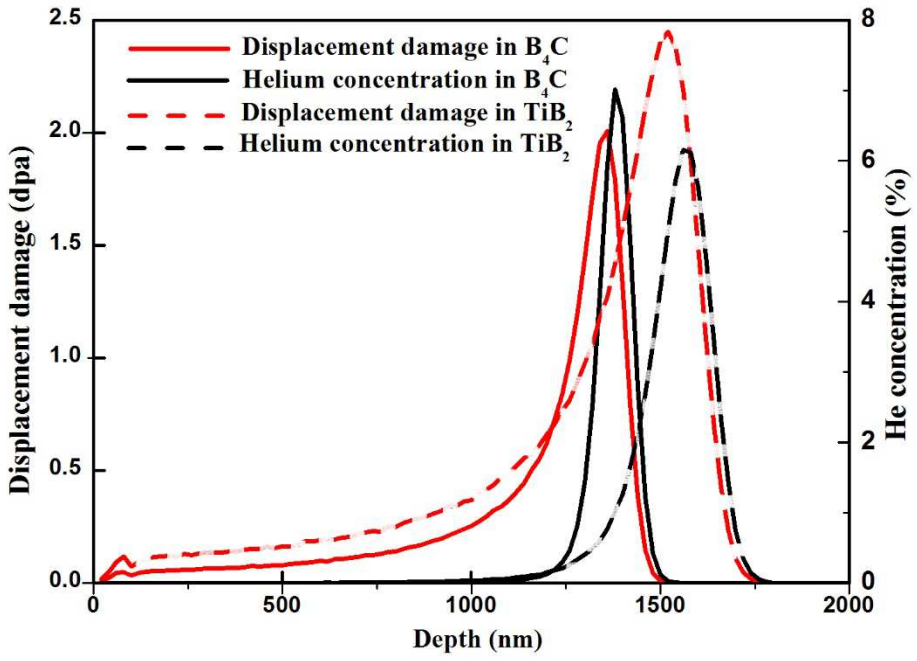
	Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)		Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)		Density (kg/m^3)	
Temperature (K)	773	1273	773	1273	773	1273
B_4C	20.00	11.00	1680.80	2072.68	2550	2550
TiB_2	81.00	78.10	1073.00	1186.00	4450	4390

614

615 Table 3. Comparison of the results calculated from real composite
616 structure models (CM), equivalent homogeneous models (HM) and the
617 relative error (RE).

Time	S1			S2			S3		
(μs)	CM(K)	HM(K)	RE(%)	CM(K)	HM(K)	RE(%)	CM(K)	HM(K)	RE(%)
0.2	819	836	2.1	832	856	2.9	867	901	3.9
0.4	917	948	3.4	941	981	4.3	997	1043	4.6
0.6	996	1033	3.7	1024	1069	4.4	1093	1129	4.2
0.8	1057	1093	3.7	1085	1128	4.0	1142	1180	3.3
1	1102	1137	3.2	1130	1168	3.4	1181	1212	2.6

618



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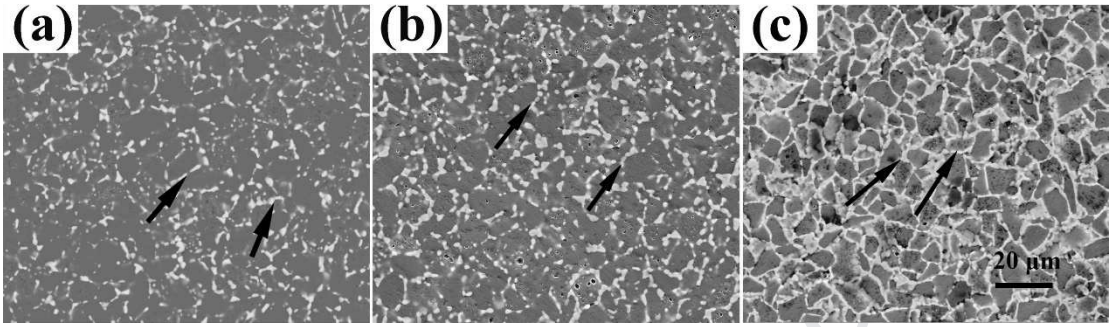

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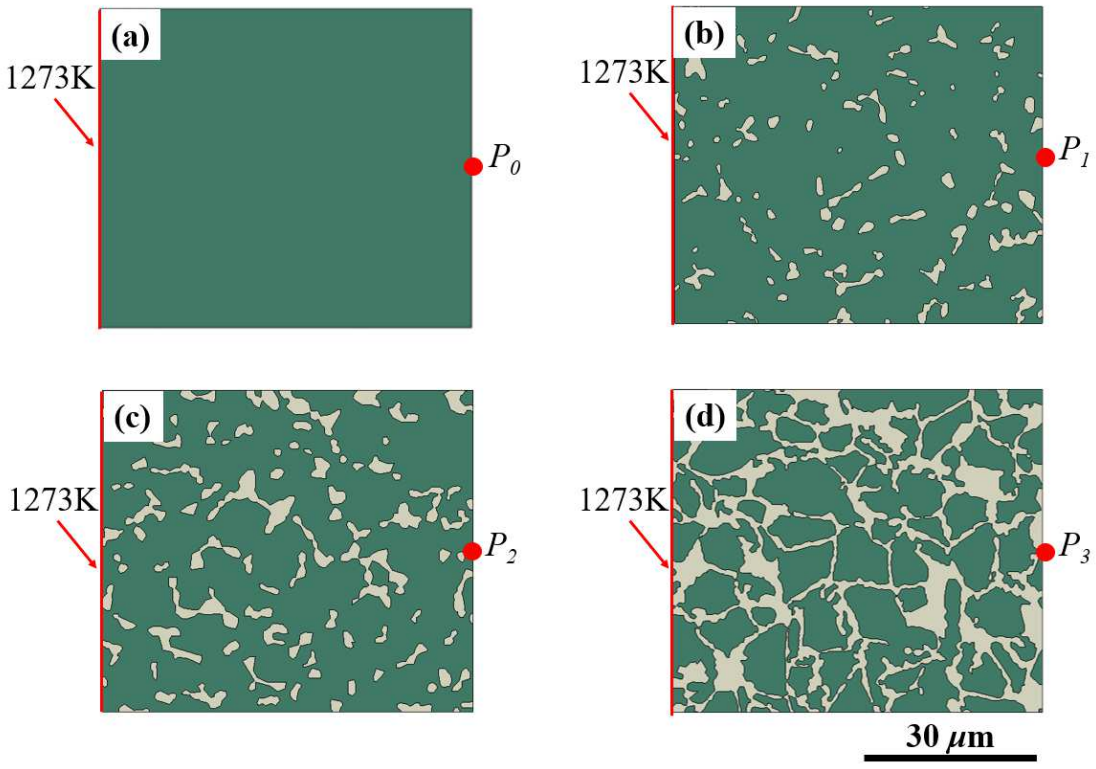

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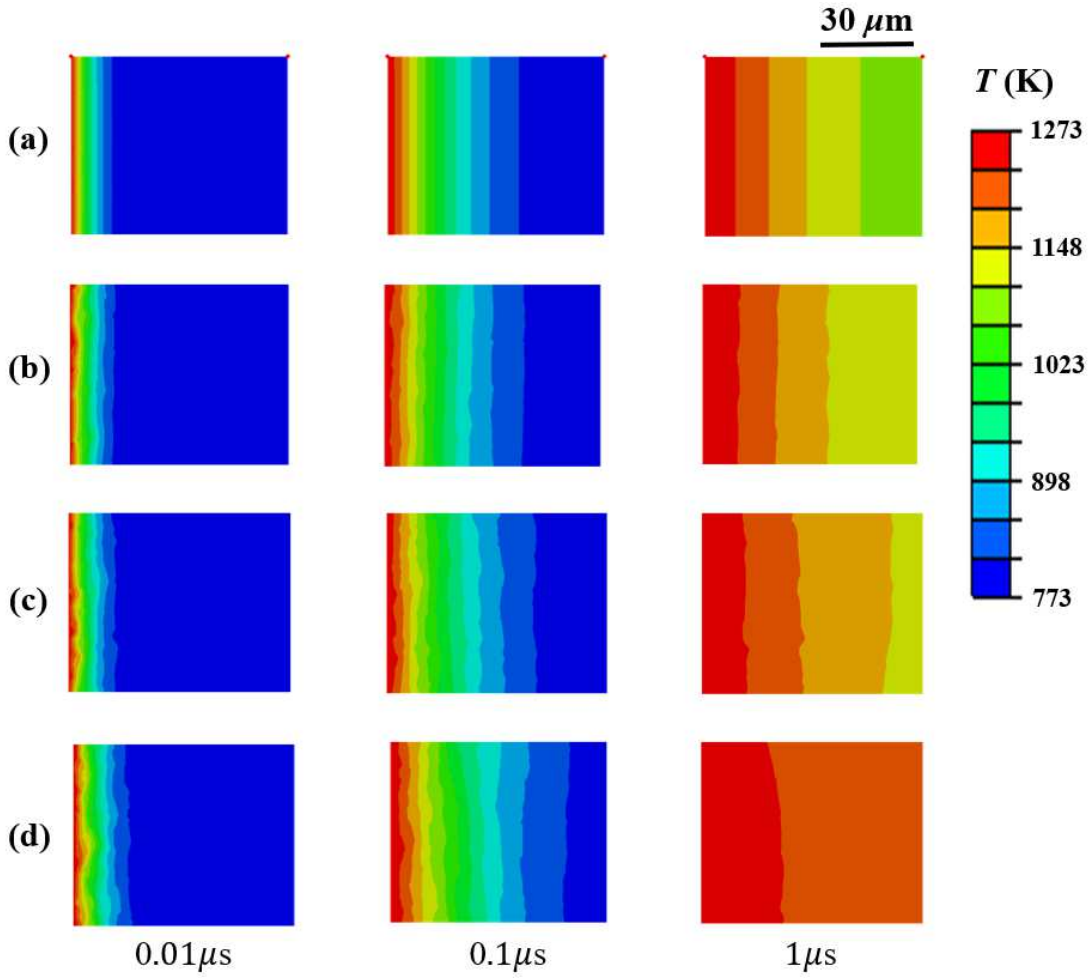

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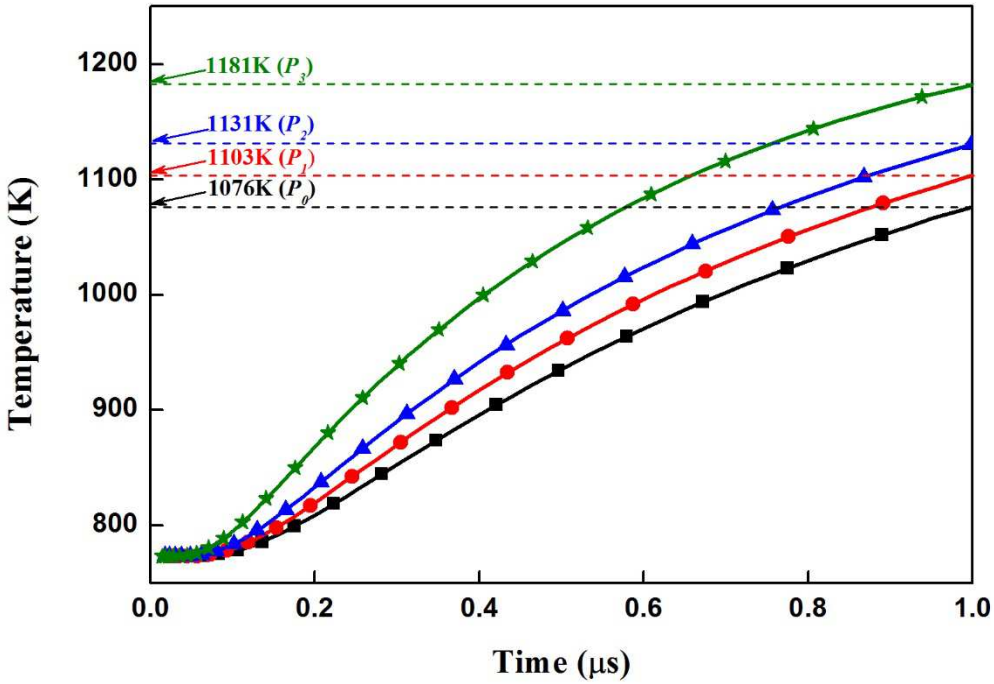

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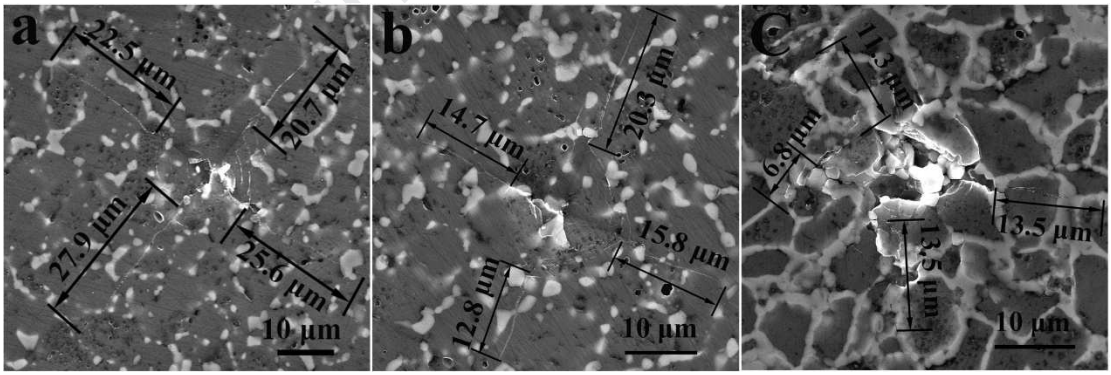

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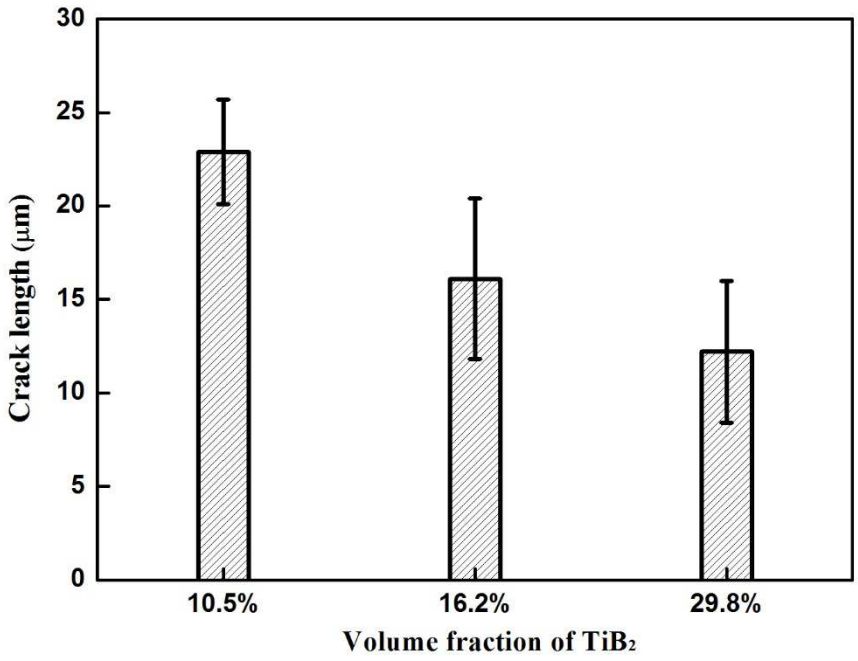

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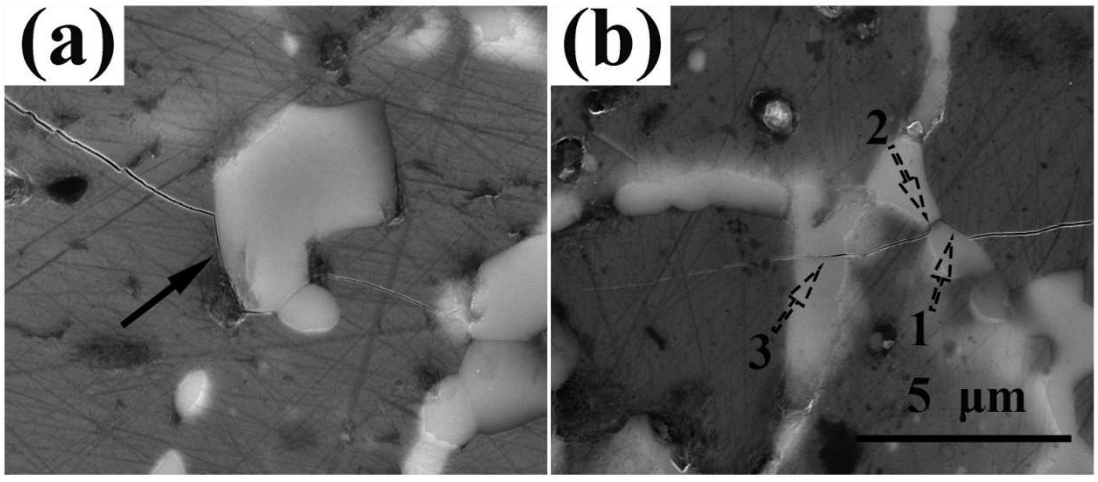

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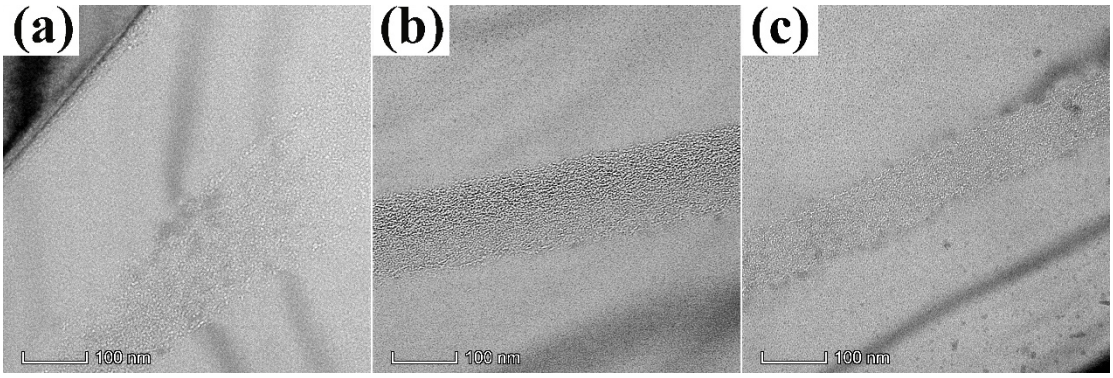

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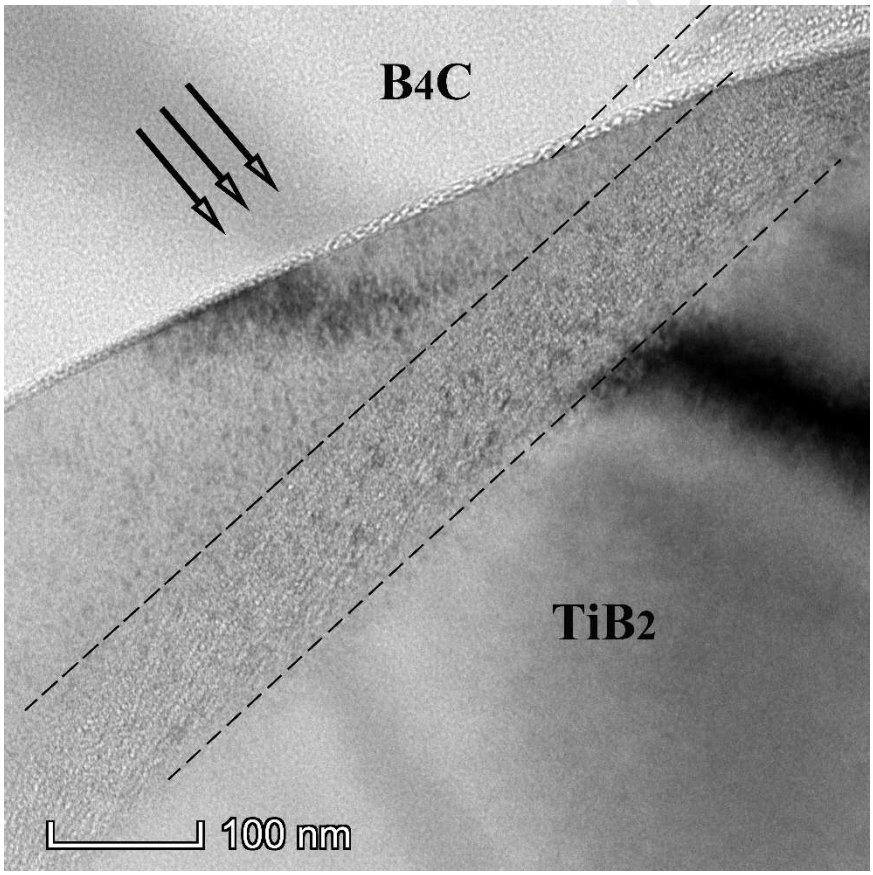

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B_4C–TiB_2 composites with B_4C grains encapsulated by TiB_2 network (cages) are fabricated.

TiB_2 network (cages) greatly improve thermal conductivity and fracture toughness of B_4C–TiB_2 composites.

The interconnected interfaces between TiB_2 network (cages) and B_4C grains act as effective sinks for the aggregation of He atoms.

Declaration of interests

☑ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: